Dynamical Climatology

Some comparisons between the middle atmosphere dynamics of the southern and northern hemispheres.

by

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DCTN 60

October 1987

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DYNAMICAL CLIMATOLOGY TECHNICAL NOTE NO. 60

SOME COMPARISONS BETWEEN THE MIDDLE ATMOSPHERE DYNAMICS OF THE SOUTHERN AND NORTHERN HEMISPHERES

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A paper presented at the Middle Atmosphere of the Southern Hemisphere Workshop, Adelaide, May 1987

Submitted for publication in Pure and Applied Geophysics.

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October 1987

Note: This paper has not been published. Permission to quote from it should be obtained from the Assistant Director of the above Meteorological Office branch.

Abstract

Comparisons are drawn between certain middle atmosphere dynamical processes in the southern hemisphere and the northern hemisphere. Attention is focused on the zonal-mean climatological state, stationary waves, transient waves of various types, stratospheric sudden warmings and polar ozone minima. Observations of the similarities and differences between the hemispheres are mentioned, and ways in which these comparisons may be used to enhance our dynamical knowledge of the whole middle atmosphere are discussed.

1. Introduction

The middle atmosphere of the southern hemisphere has in the past received much less attention from dynamical meteorologists than its northern hemisphere counterpart. A major reason for this state of affairs has been the comparative lack of global-scale data for the southern hemisphere. However, with the advent of satellite measurements this imbalance has been greatly reduced. It is the purpose of the Middle Atmosphere of the Southern Hemisphere (MASH) program to bring our understanding of the middle atmosphere of the southern hemisphere to a level comparable with that of the northern hemisphere.

There are several reasons for focusing on the southern hemisphere middle atmosphere. The most obvious is that it comprises half of the middle atmosphere, and displays a number of phenomena that are not present, or are not so prominent, in the northern hemisphere. Moreover, to the extent that the hemispheres are independent (an assumption that must be used with caution), they can be regarded as two separate systems for testing our general understanding of middle atmosphere processes. Thus by comparing and contrasting the middle atmosphere in the northern hemisphere and southern hemisphere, we may expect to enhance our knowledge of the middle atmosphere as a whole.

Before discussing these issues, it is worth digressing briefly to consider the relationship between the two main tools of middle atmosphere study: observations and models. It is important to recognise the difficulty, if not impossibility, of inferring causal relationships between atmospheric processes solely on the basis of observations, even if sophisticated diagnostics are used to process these data. Cause-and-effect mechanisms must be established by means of controlled experiments, and these cannot be performed on the

large-scale atmosphere itself. Some hints may perhaps be conveyed by comparison of similar states at different times or in different hemispheres, but the only real opportunity for such experiments is afforded by models of the atmosphere. Ideally, one would wish to employ a whole hierarchy of models, ranging from simple (perhaps analytical) models through to the most complex general circulation models. Models are also needed for testing the interpretation and usefulness of diagnostics. A thorough understanding of causal mechanisms is not only of basic scientific importance but also a necessary foundation for the construction of reliable models for the prediction of the future behaviour of the middle atmosphere.

The first purpose of this paper is to draw some simple comparisons between the observed structure (mostly large-scale) of the middle atmosphere in the two hemispheres. The second aim is to provide a focus for some possible MASH-related projects by raising a few simple questions concerning the ways in which these comparisons may be studied and exploited.

2. Comparisons between observations of the two hemispheres

a. Climatological zonal means

The most basic quantities that can usefully be compared between the two hemispheres are probably the climatological zonal means. We here present the climatological monthly zonal means of temperature T and geostrophic zonal wind u_g compiled by Barnett and Corney (1985) from five years of satellite data. We concentrate on the months of January, April, July and October. Note that the five-year averaging means that interesting features from individual years may be lost by being smoothed out.

Looking first at temperatures for the summer months (January, southern hemisphere; July, northern hemisphere) in Fig. 1a, we see that there is a close resemblance between the two hemispheres, with a cold equatorial tropopause (temperatures below 200 K), a warm, quasi-horizontal stratopause (peaking at over 280 K at the pole) and cold polar regions above 80 km altitude in each. In winter, however, (July, southern hemisphere; January, northern hemisphere: Fig. 1b) significant interhemispheric differences appear. While the stratopause tilts upwards towards the winter pole in both hemispheres, that in the southern hemisphere is a little higher in altitude and

some 20 K warmer than that in the northern hemisphere. On the other hand the southern winter lower stratosphere is some 20 K cooler than the northern. In spring (Fig. 1c) the stratopause is fairly flat, but noticeably warmer at the south pole than at the north pole. Moreover the zonal-mean temperature at about 40 km altitude is significantly cooler at 50°S than at the pole (Barnett, 1974), while no such "cool collar" is observed in the northern hemisphere spring climatology. The temperatures in the two hemispheres are fairly similar in autumn (Fig. 1d) although the southern lower stratosphere is somewhat cooler (by about 4K at 80° latitude and 30 mb) than the northern.

Comparable interhemispheric similarities and differences occur for the geostrophic zonal winds, displayed in Fig. 2; this is to be expected from the thermal wind relationship. Thus the summer winds in Fig. 2a are generally easterly (westward) in both hemispheres of the middle atmosphere above about 20 km (except in high southern latitudes). They both peak at just over 60 m s^{-1} at about 70 km altitude, and decrease above that level. On the other hand there are significant differences between the winter westerlies (Fig. 2b), which reach 100 m s^{-1} at about 50 km altitude and 42° in the southern hemisphere, but only about 60 m s^{-1} at about 68 km and 35° in the northern hemisphere. Winds in spring are fairly weak, both easterly and westerly, in both hemispheres (Fig. 2c), the main features of note being a westerly jet in the southern lower stratosphere. Autumn winds (Fig. 2d) are fairly symmetric about the equator, and mostly westerly, although reaching somewhat larger magnitudes in the southern hemisphere.

One should of course be cautious about drawing general conclusions from this limited selection of data. For example, an examination of Barnett and Corney's diagrams shows that northern hemisphere winds in December are much stronger than in January, and quite similar to the southern hemisphere winds in June: it is interesting that the large mean-flow decelerations found in the northern hemisphere upper stratosphere between December and January have no counterpart in the southern hemisphere. This fact was noted by Hartmann (1985), drawing on data from Geller et al. (1983) and from C.R. Mechoso.

b. Climatological data that are not zonally-averaged

A rather more complicated set of quantities that can be compared between hemispheres are climatological data that are not zonally-averaged, such as monthly-mean maps. As an example, Fig. 3a depicts monthly-mean maps of the

10 mb temperature field in winter (January, northern hemisphere; July, southern hemisphere). Significant differences appear: while the northern hemisphere map exhibits noticeable zonal asymmetries, with a minimum temperature of just below 210 K, the southern hemisphere chart is much more zonally-symmetric, with a lower central value (< 190 K) and correspondingly stronger latitudinal gradients. (These differences are consistent with those in Fig. 1b.) The summer charts in Fig. 3b (July northern hemisphere; January, southern hemisphere), on the other hand, are more similar and are both fairly zonally-symmetric. Similar features appear in the height fields of Fig. 4: note the off-centred northern hemisphere westerly vortex in January and the stronger but more zonally-symmetric southern hemisphere westerly vortex in July.

A more quantitative (but not necessarily more meaningful) way of representing the zonal asymmetries of the climatological data is to expand the monthly-mean data in zonal harmonics. Thus, denoting the climatological monthly mean of the geopotential Φ by $\langle\Phi\rangle$, and the zonal mean by an overbar, we can write

$$\langle\Phi\rangle = \langle\bar{\Phi}\rangle + \sum_{s\geq 1} A_s(\phi,z) \cos [\, s\lambda + \alpha_s(\phi,z) \,]$$

where A_s is the amplitude and α_s the phase of the wavenumber s harmonic, λ is longitude, ϕ is latitude and z is a height coordinate. The amplitudes and phases of these "stationary-wave" components can then be plotted in the meridional plane. Winter values (January, northern hemisphere; July, southern hemisphere) for the amplitudes of s = 1 and 2 are shown in Fig. 5. In the stratosphere, the northern hemisphere amplitudes tend to be stronger than those in the southern hemisphere, while the values are roughly comparable in the mesosphere. Summer amplitudes are much smaller in both hemispheres. Phases have a similar appearance in both hemispheres: those for s = 1 in winter are depicted in Fig. 6.

The climatological zonal asymmetries in January in the northern hemisphere are often regarded as due to the presence of stationary waves. This physical interpretation should be treated with caution, but nevertheless some progress can be made in modelling the zonal asymmetries using linear stationary-wave models: see §3b.

c. Transient planetary waves

Examination of middle atmosphere data that are neither climatologically nor zonally averaged shows a great deal of transient, zonally-asymmetric activity. Some of this activity has been interpreted in terms of travelling disturbances with various time and space scales (see, e.g., Salby 1984). The most well-known travelling wave is the "five-day wave", which was first noted in tropospheric data and has also been detected in the middle atmosphere. This is a westward travelling wave with period close to 5 days, which is roughly sinusoidal in the east-west direction with zonal wavenumber 1. Temperature and geopotential amplitudes are approximately symmetric about the equator in the troposphere and lower stratosphere, but become more asymmetric in the upper stratosphere (being larger in the summer hemisphere). In addition to this 5-day wave, some rather less prominent travelling modes have been identified by careful time and space filtering of data.

In some respects the southern hemisphere, having less stationary-wave activity than the northern, is a "cleaner" environment in which to see these travelling disturbances. One interesting example is the coherent "warm pool" found in satellite radiance data for the upper stratosphere by Prata (1984), which encircles the south pole several times, with a period of about 4 days. Another southern hemisphere case is the slowly eastward-travelling wavenumber 2 component noted by several authors (e.g. Harwood 1975, Mechoso et al. 1987), which has a period of 2-3 weeks. In neither of these two examples are the dynamics particularly well understood at present.

A rather different type of transient process is the "breaking planetary wave". This name was given by McIntyre and Palmer (1983,1984,1985) to large-scale, large-amplitude disturbances in which nonlinear advection leads to the rapid, irreversible distortion of air masses. Breaking planetary waves are quite well depicted in quasi-horizontal isentropic maps of Ertel's potential vorticity (a quasi-conservative tracer), where blobs of potential vorticity may be pulled out of the main stratospheric vortex and stretched into long, thin filaments. Such events appear to be quite common in the middle and upper stratosphere, where upward-propagating quasi-stationary planetary waves attain large amplitudes, mainly because of the decreasing air density. Their nonlinear dynamics are not yet well understood, and high-resolution numerical simulation will be an essential part of their study. (See Juckes and McIntyre 1987 for a recent investigation.)

d. Stratospheric sudden warmings

Stratospheric sudden warmings are the most spectacular large-scale dynamical events to take place in the middle atmosphere; they occur in winter, and involve rapid rises of temperature in the polar stratosphere. These temperature changes result in a reversal of the latitudinal gradient of the zonal-mean temperature (at 10 mb and below, and poleward of 60° latitude, according to the WMO definition of sudden warmings). They are also associated with a deceleration of the zonal-mean westerly zonal wind in this region. If the winds reverse to become easterly, the warming is called "major"; if not, it is called "minor".

There is considerable interannual and interhemispheric variability in the occurrence and morphology of sudden warmings. Major warmings occur on average in about one in two northern hemisphere winters, but have never been observed in the southern hemisphere winter. Strong minor warmings have been observed in both hemispheres; in the southern hemisphere they tend to be confined to the middle and upper stratosphere, whereas in the northern hemisphere they usually occur in the lower and middle stratosphere.

After some sudden warmings the polar temperature falls again and the zonal winds accelerate, with the zonal-mean state reverting to roughly its previous form. Towards the end of winter, however, some warmings lead directly into the change-over to summer conditions of warmer polar temperatures and easterly zonal winds: such warmings are called "final warmings". An interhemispheric comparison of the final warmings in 1982 is given by Yamazaki (1987). He finds that the final warming in the southern hemisphere in October is stronger and more rapid than that in the northern hemisphere at the end of March. The two events also differ in their detailed structure and evolution.

e. Polar ozone distributions

Although it is the antarctic "ozone hole" that is currently receiving intensive investigation, following the work of Farman et al. (1985), comparatively low values of ozone (< 3 ppmv at 10 mb) were noted in the LIMS (Limb Infrared Monitor of the Stratosphere) data by Leovy et al. (1985) over the north pole in October 1978. However, these authors found that this northern "ozone hole" was filled in, and the total ozone column increased, during the course of the winter by tongues of ozone-rich air moving into the polar

regions from low latitudes at the time of large-amplitude "breaking planetary-wave" events.

By contrast, the south polar winter vortex seems to consist of a much more coherent air mass, which is not disturbed by events of this type. (This fact is also manifested in the comparisons of the monthly-mean vortices discussed in §2b.) It appears, therefore, that meridional transport cannot significantly increase the antarctic ozone column in winter, and other mechanisms -- whether chemical or dynamical -- have the opportunity to deplete it instead.

f. Other features for comparison

There are several other areas in which interhemispheric comparison of data has scarcely begun: these include comparison of gravity-wave characteristics (as measured by radars and lidars, for example), atmospheric tides, and further aspects of tracer transport and interannual variability. There is a clear need for additional data and (perhaps more importantly) more extensive analysis of existing data sets.

3. Examination and exploitation of the interhemispheric differences

a. The climatological zonal-mean state

A basic scientific question that provides a useful focus for discussion of the climatological zonal-mean state is "how is this state maintained ?". A quick answer, which seems to be a reasonable first approximation to the truth, is that it is maintained by a competition between radiative and dynamical effects (e.g. Fels 1985; Andrews 1987). A "radiative spring" tries to pull the zonal-mean state towards a hypothetical state of radiative balance (Fels 1985; Shine 1987): this spring is opposed by dynamical processes, particularly rectified nonlinear eddy effects (expressed, roughly speaking, by the Eliassen-Palm flux divergence). This dynamical driving manages to keep the observed zonal-mean state significantly different from the radiative state in the winter stratosphere and in the upper mesosphere, but not in the summer stratosphere or lower mesosphere. The relevant eddies are likely to be mainly planetary waves (stationary or breaking) in the winter stratosphere and breaking gravity waves (and perhaps tides, to a lesser extent) in the upper mesosphere. Gravity waves may also play a role in the stratosphere.

In general, the hypothetical radiatively-determined state in the southern hemisphere is quite similar to that at the corresponding season in the northern hemisphere (K.P. Shine, personal communication 1987); thus inter-hemispheric differences in the zonal-mean climatology must be mainly associated with differences in the eddy-induced forcing. In particular it seems likely that the differences in winter stratospheric temperatures, noted in §2a, are associated with the weaker southern hemisphere planetary waves, which are less able to keep temperatures well above the cold radiative value than are their stronger northern hemisphere counterparts. By contrast, it appears that the upper mesospheric gravity-wave forcing must be quite similar in the northern hemisphere and the southern hemisphere: see §3d.

Of course this simple picture of the radiative-dynamical interactions is incomplete is some respects: in particular, the eddy driving cannot be thought of as independent of the mean flow, since in general the wave properties can be expected to be modified by the flow through which they propagate. This implies a two-way interaction between eddies and mean state that leads to the possibility of subtle and complex feedbacks, and also makes for difficulties in sorting out cause-and-effect relationships.

An example of this kind of interactive process was pointed out by Dr R.A. Plumb (personal communication 1986). The weaker southern hemisphere winter planetary waves are unable to force the zonal-mean temperature $\overline{T}$ far from the cold radiatively-determined value T_r, and hence (by the thermal-wind relationship) allow strong zonal-mean westerlies (see Figs. 1b and 2b). The stronger jets in turn allow little (stationary) planetary wave activity to propagate into the southern stratosphere from the troposphere, by the Charney-Drazin (1961) criterion, or a generalization of it. Conversely the stronger winter planetary waves in the northern hemisphere drive the stratospheric temperatures to a much warmer value than the radiative T_r, and likewise keep the zonal westerlies weaker. These winds allow more tropospheric planetary wave activity into the stratosphere. The two hemispheres may thus represent two different kinds of wave-mean balance; in neither hemisphere can one clearly identify whether the wave-forcing of the mean flow or the mean-flow modification of the waves is the controlling influence. The situation is reminiscent of the "multiple-equilibrium" scenarios currently being invoked in some areas of tropospheric research (see, e.g., Benzi et al., 1986). A qualitatively similar two-state behaviour has also been found in the stratosphere during

"perpetual January" general circulation model experiments by Boville (1986, especially pp. 1723-1724). A whole range of models, simple and complex, will probably be needed to elucidate such processes in detail.

A number of observational studies have been directed towards documenting interactions between the zonal-mean flow and the eddies in the middle atmosphere on various timescales. An example that concentrates particularly on the quite complicated interhemispheric differences in these processes is that of Shiotani and Hirota (1985).

b. Planetary waves

A large number of linear models have contributed to our understanding of the dynamics of planetary waves. The more complex models of this type specify zonal-mean background winds $\bar{u}(\phi,z)$ and temperatures $\bar{T}(\phi,z)$ that bear a reasonable resemblance to climatology. In the case of stationary waves, orographic and thermal forcing is prescribed at the lower boundary. The generally weaker orographic forcing in the southern hemisphere may be one reason for the weaker stratospheric planetary waves there (another being the stronger zonal winds, as mentioned above). Explanations of the observed travelling waves are generally based on the existence of unforced normal modes of the linear equations (together with appropriate boundary conditions). Some of these explanations (e.g. of the 5-day wave) have been quite successful, and can account not only for the period but also for such secondary features as the difference in amplitude between summer and winter hemispheres noted in §2c. The observed waves may also involve instabilities, although the linear theory can here only explain a period of growth before nonlinearities set in.

There is now an increasing need for more study of nonlinear processes associated with planetary waves. These processes include the planetary-wave "breaking" mechanism and also the nonlinear behaviour of unstable disturbances. The southern hemisphere provides some interesting examples, such as the possibility of instabilities growing and then perhaps equilibrating on radiatively-forced barotropically unstable flows in the polar upper stratosphere.

We can conclude from this subsection and the previous one that it may be necessary to seek joint explanations of interhemispheric differences in the climatological zonal flow and the planetary waves. This is in any case

consistent with the fact that the "zonal mean, eddy" separation can be an artificial one, especially when the "eddies" are of large amplitude.

c. The dynamics of sudden warmings

Since the paper of Matsuno (1971), a large body of theory has been developed to explain sudden warmings in terms of "wave, mean-flow interaction" mechanisms. It is suggested that planetary waves, propagating up from the troposphere, are focused into the polar cap in the stratosphere and, by rectified nonlinear effects, bring about rapid mean-flow changes there. It is not clear whether the infrequent occurrence of sudden warmings is due to the need for unusually large tropospheric forcing or to the requirement of an unusual configuration of the stratospheric mean state, perhaps resulting from earlier wave events.

This theory is partly based on "weakly nonlinear" arguments, and while it successfully accounts for certain aspects of observed and modelled warmings it still cannot fully explain some features of major warmings and strong minor warmings, when the flow is highly distorted and the "waves" are strongly nonlinear. There is plenty of scope for observational and theoretical study, and here comparison between the hemispheres may be useful. For instance is the absence of major warmings in the southern hemisphere due mainly to the stronger winter westerlies there (which would need to decelerate more than the weaker northern hemisphere westerlies in order to reverse) or to weaker tropospheric forcing of planetary waves; or are both of these elements inextricably linked in any case ?

d. The large-scale effects of gravity waves

It was mentioned in §3a that departures from radiative balance in the upper mesosphere are thought to be mainly due to breaking gravity waves. Much research on breaking gravity waves has been carried out in recent years, following the paper of Lindzen (1981), but their fully nonlinear mechanics when amplitudes reach "saturation" values are still far from well-understood. In complex processes like this, every avenue of research should be explored, and diagnostic studies of the observed atmosphere, in conjunction with conceptual and quantitative models, may well be of value. For example an indirect estimate, based on satellite data, of the eddy-forcing required to maintain the current climatology of the mesosphere may help us to better understand the large-scale effects of breaking gravity waves. My colleagues

Drs K.P. Shine and C.J. Marks are currently investigating this possibility.

An interesting point in this regard was made by Dr R.A. Plumb at the Adelaide MASH workshop: the close similarity at all seasons (except perhaps in winter) between the two halves of the upper mesosphere in Fig. 1 suggests (if current theory is to be believed) that the gravity-wave forcing of the mean flow is very similar in the two hemispheres. This is despite the probable differences in magnitudes of the generation mechanisms for the waves at lower levels, and the differing environments through which the waves have propagated to reach the upper mesosphere. The comparison may be giving us valuable clues to the gravity wave saturation mechanisms and the resultant driving of the mean flow by the waves.

e. Polar vortices

Even though the primary cause of the observed long-term depletion of antarctic ozone seems likely to be the increase of man-made chlorine compounds in the atmosphere (e.g. Pyle and Farman, 1987), a full understanding of the process will require a clearer picture of the dynamical state of the antarctic stratosphere under which the chemical destruction mechanisms occur. As noted in §2e, the south polar winter vortex seems much less disturbed by planetary-wave events than its northern counterpart. This is presumably partly related to the comparative weakness of the southern hemisphere planetary-wave activity. Further possible dynamical reasons for the resilience of the antarctic stratospheric vortex are discussed by Juckes and McIntyre (1987).

4. Conclusion

This paper has been more concerned with raising questions and suggesting avenues for future research than supplying any definitive answers. It has pointed out some areas in which comparisons between the two hemispheres may perhaps be exploited to extend our understanding of the middle atmosphere as a whole. These comparisons have of course to be put into the context of the methods used for atmospheric study, involving a careful combination of observational data and theoretical modelling. An important use of models is to test hypotheses, and it is possible that the observed differences between the two hemispheres may help provide sharper hypotheses for models to test.

One caveat that must be borne in mind, however, is that the northern and southern hemispheres are not totally independent. A further important topic for future research is the investigation of the extent to which the two are coupled, for example by cross-equatorial wave propagation and interhemispheric transport of tracers.

Acknowledgements

I wish to thank C.J. Marks, A. O'Neill, R.A. Plumb and K.P. Shine for helpful discussions, and H. Cattle for some constructive comments on an earlier version of the manuscript. J.J. Barnett and M. Corney kindly provided the diagrams. I am most grateful to the MASH Organizing Committee and Monash University for providing travel funds that enabled me to attend the Adelaide Workshop.

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Figure captions

Fig. 1. Monthly and zonally averaged temperature (K) at corresponding seasons in the two hemispheres, based on a five-year climatology. (a) summer, (b) winter, (c) spring, (d) autumn. (Adapted from Barnett and Corney, 1985.)

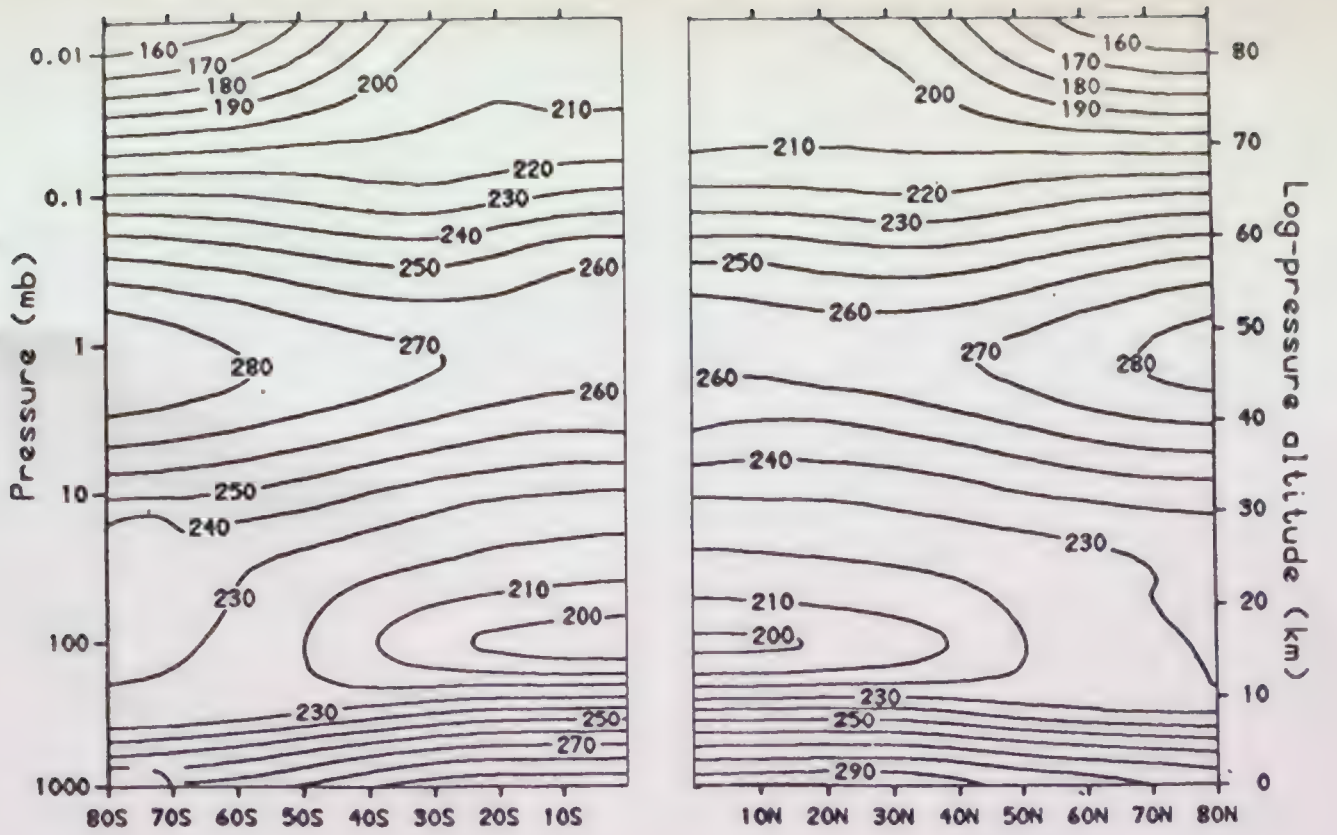
Fig. 2. As for Fig. 1, but showing geostrophic zonal winds in m s^{-1} (eastward winds positive, westward winds negative). (a) summer, (b) winter, (c) spring, (d) autumn. (Adapted from Barnett and Corney, 1985.)

Fig. 3. Polar stereographic maps of monthly averaged temperature (K) at 10 mb (approximately 30 km altitude) at corresponding seasons in the two hemispheres: (a) winter, (b) summer. (Courtesy of J.J. Barnett and M. Corney, Department of Atmospheric Physics, Oxford University.)

Fig. 4. As for Fig. 3, but showing 10 mb geopotential height field $\langle\Phi\rangle/g$ (g = 9.8 m s^{-2}) in decametres. Arrows indicate direction of geostrophic flow. (a) winter, (b) summer. (Courtesy of J.J. Barnett and M. Corney, Department of Atmospheric Physics, Oxford University.)

Fig. 5. Amplitude (decametres) of the monthly-mean geopotential height field in winter for (a) wavenumber 1 and (b) wavenumber 2. (Adapted from Barnett and Corney, 1985.)

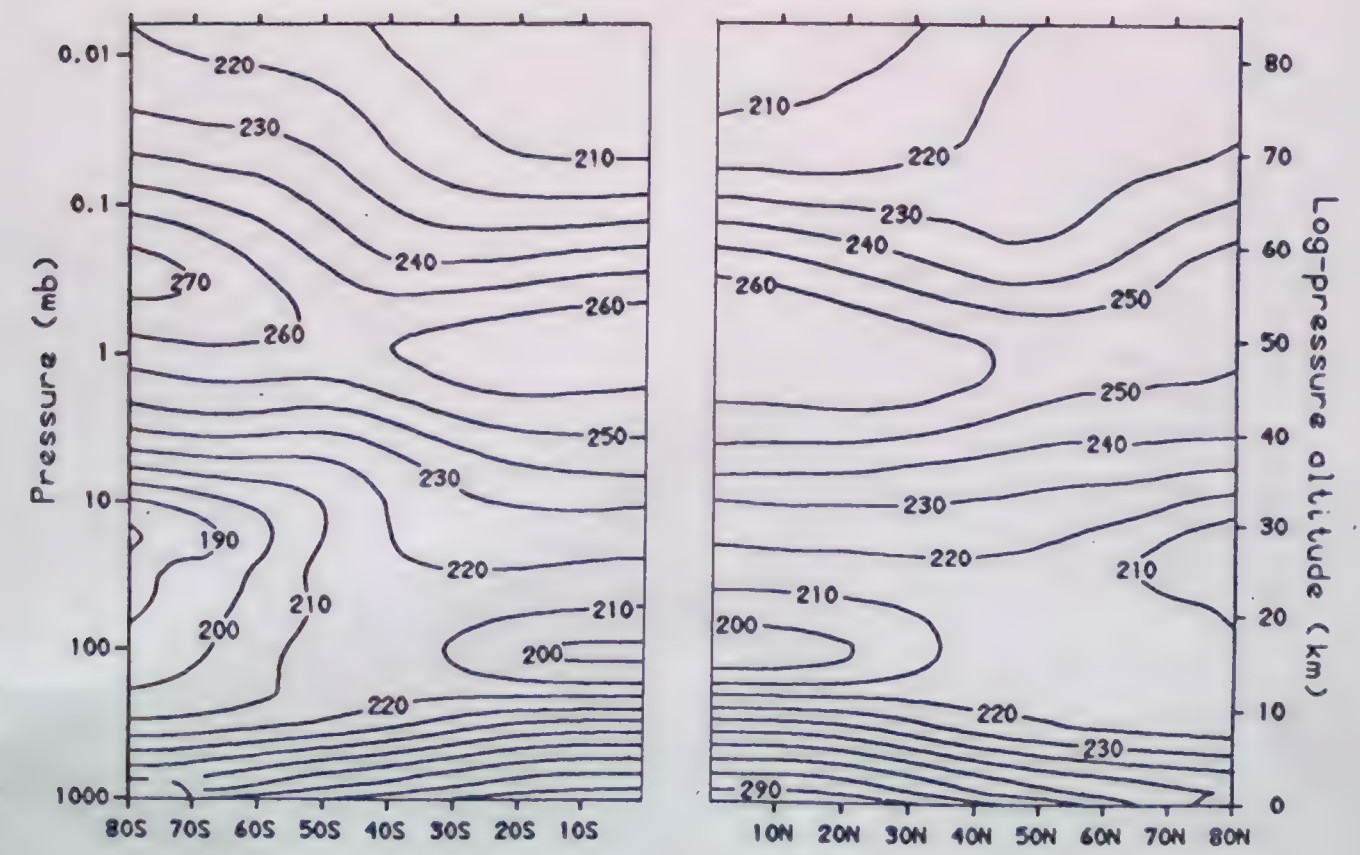
Fig. 6. Negative phase $-\alpha_1$ (degrees) of monthly-mean geopotential height for wavenumber 1 in winter. (Adapted from Barnett and Corney, 1985.)



Southern hemisphere: January

Northern hemisphere: July

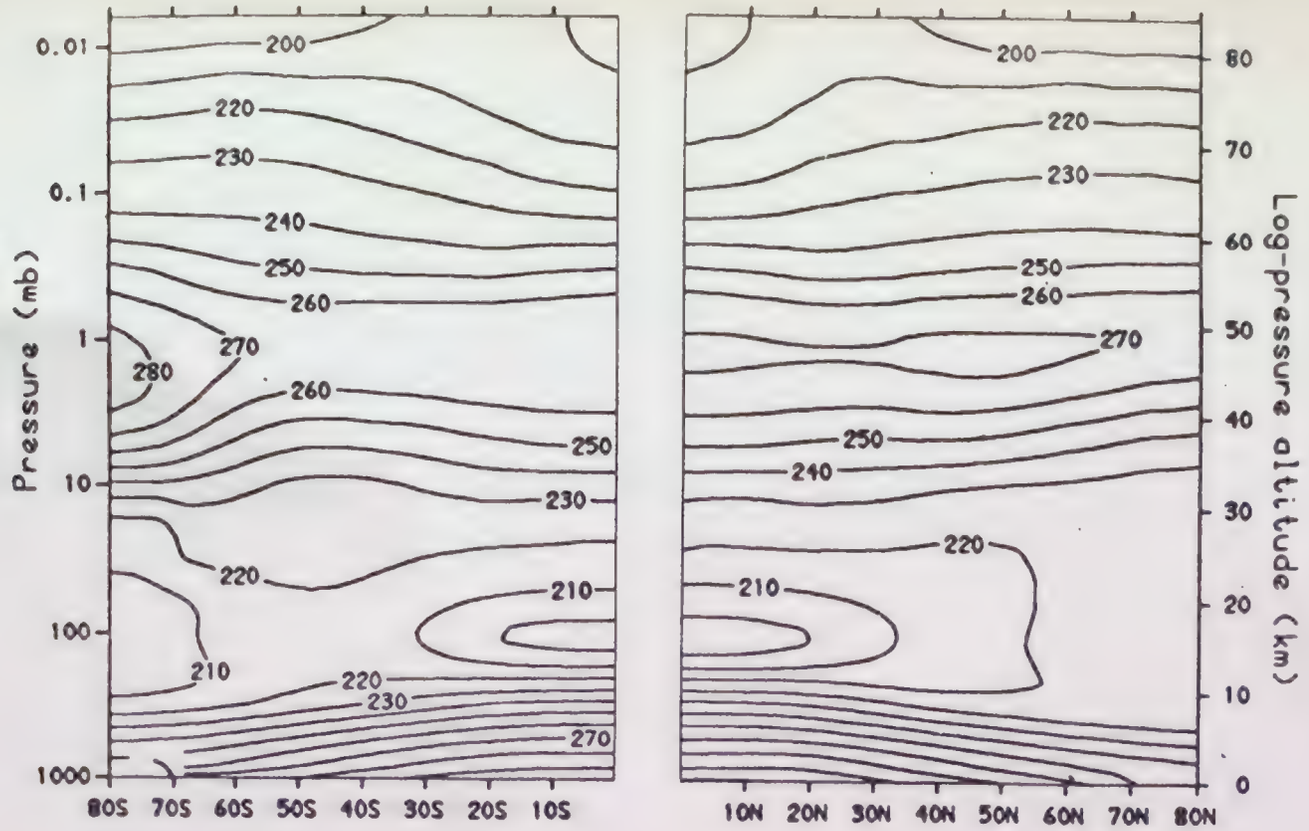
Fig 1a



Southern hemisphere: July

Northern hemisphere: January

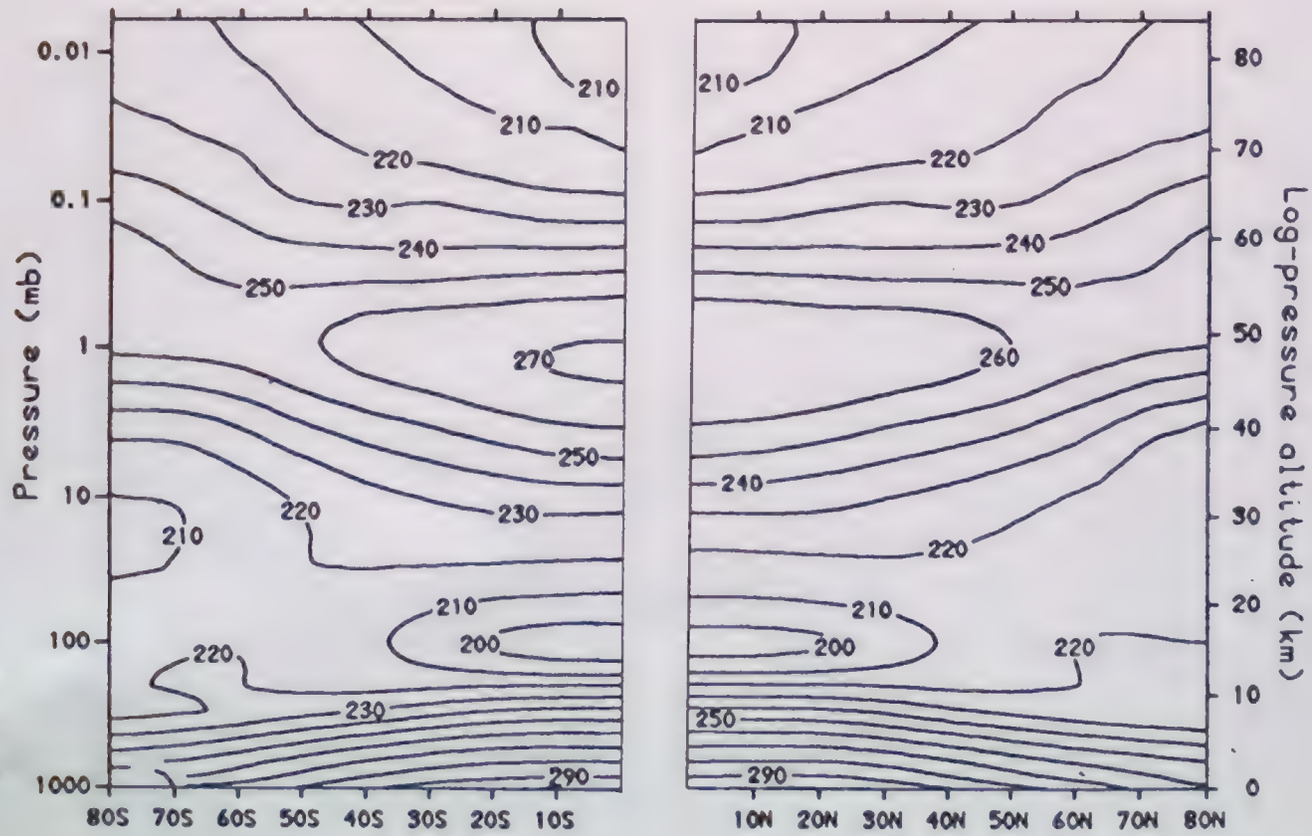
Fig 1b



Southern hemisphere: October

Northern hemisphere: April

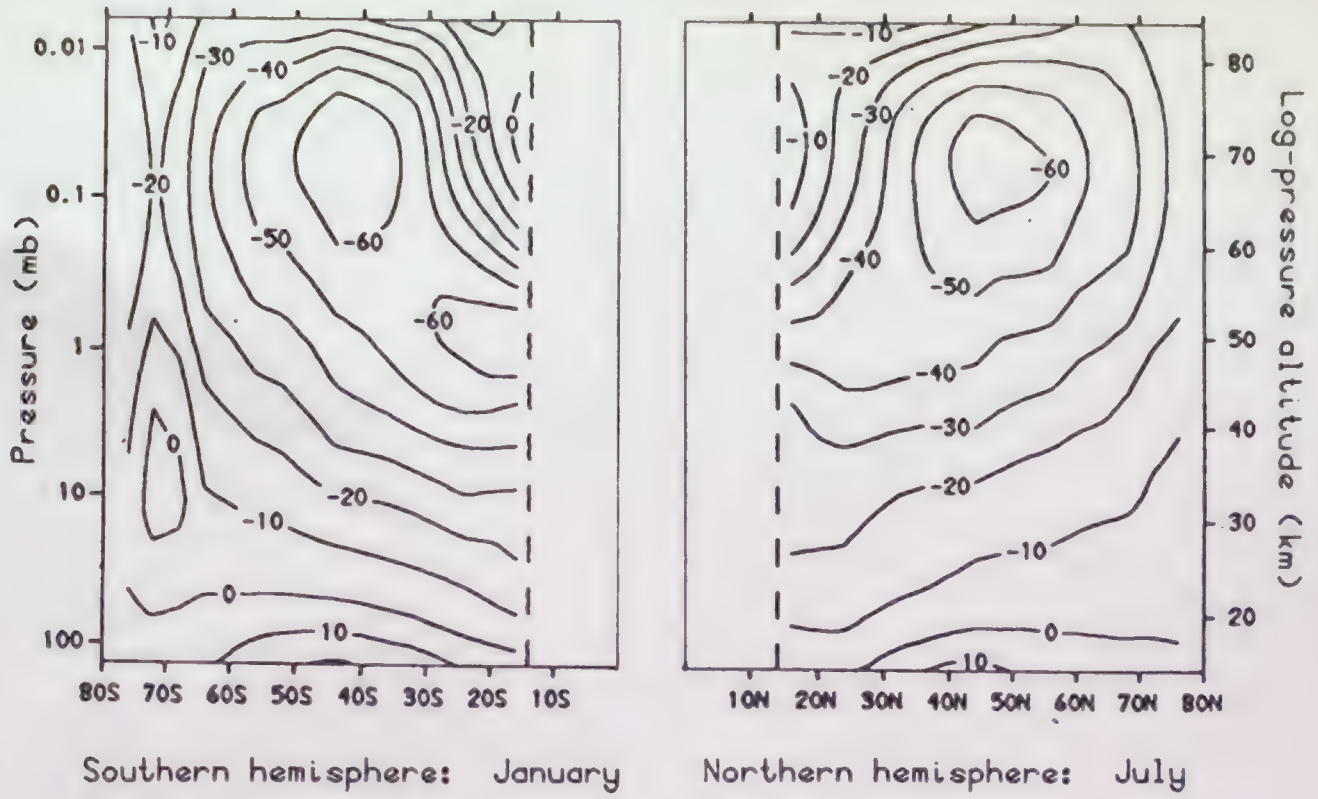
Fig 1c



Southern hemisphere: April

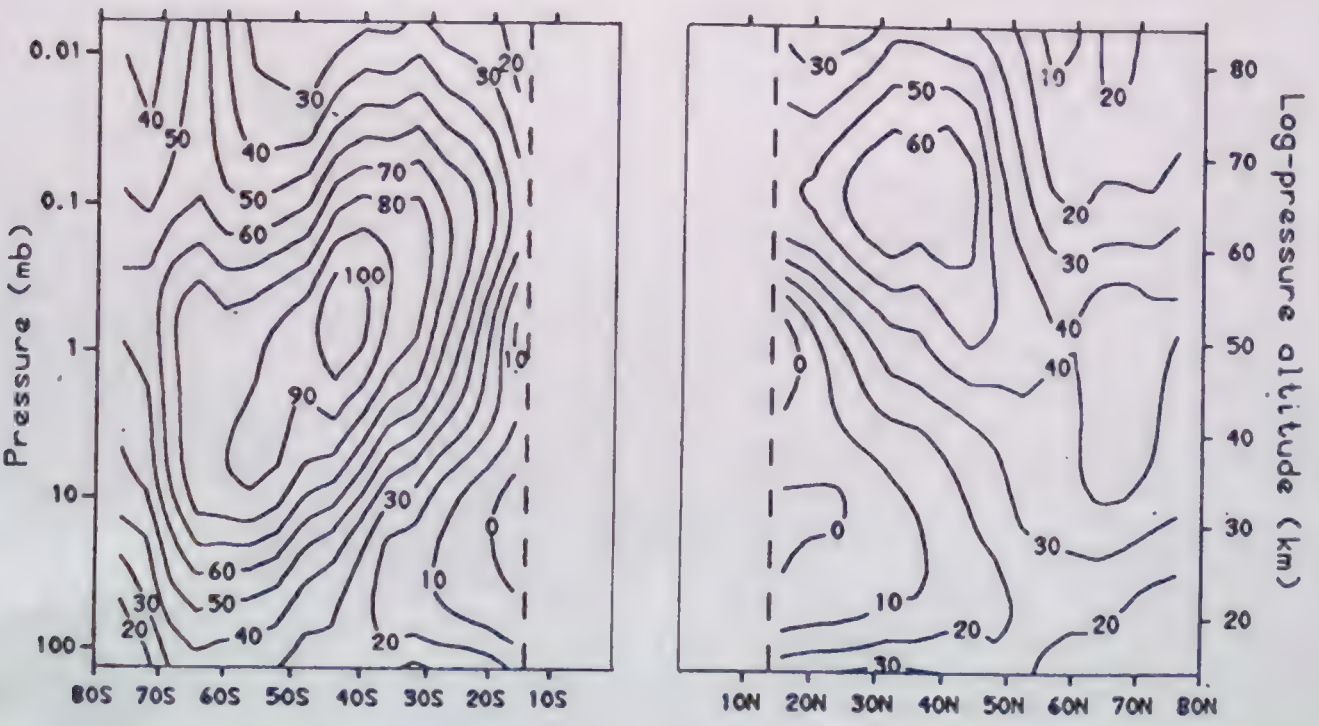
Northern hemisphere: October

Fig 1d



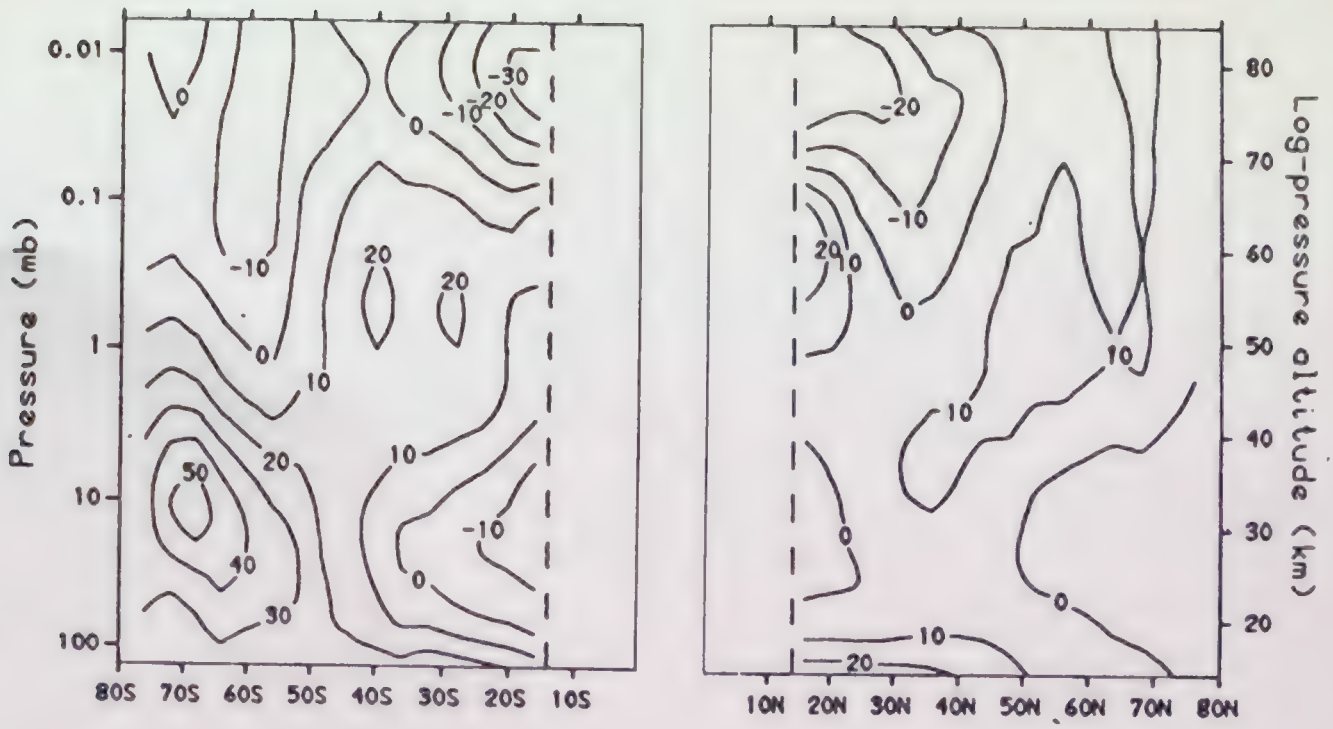
Southern hemisphere: January Northern hemisphere: July

Fig 2a



Southern hemisphere: July Northern hemisphere: January

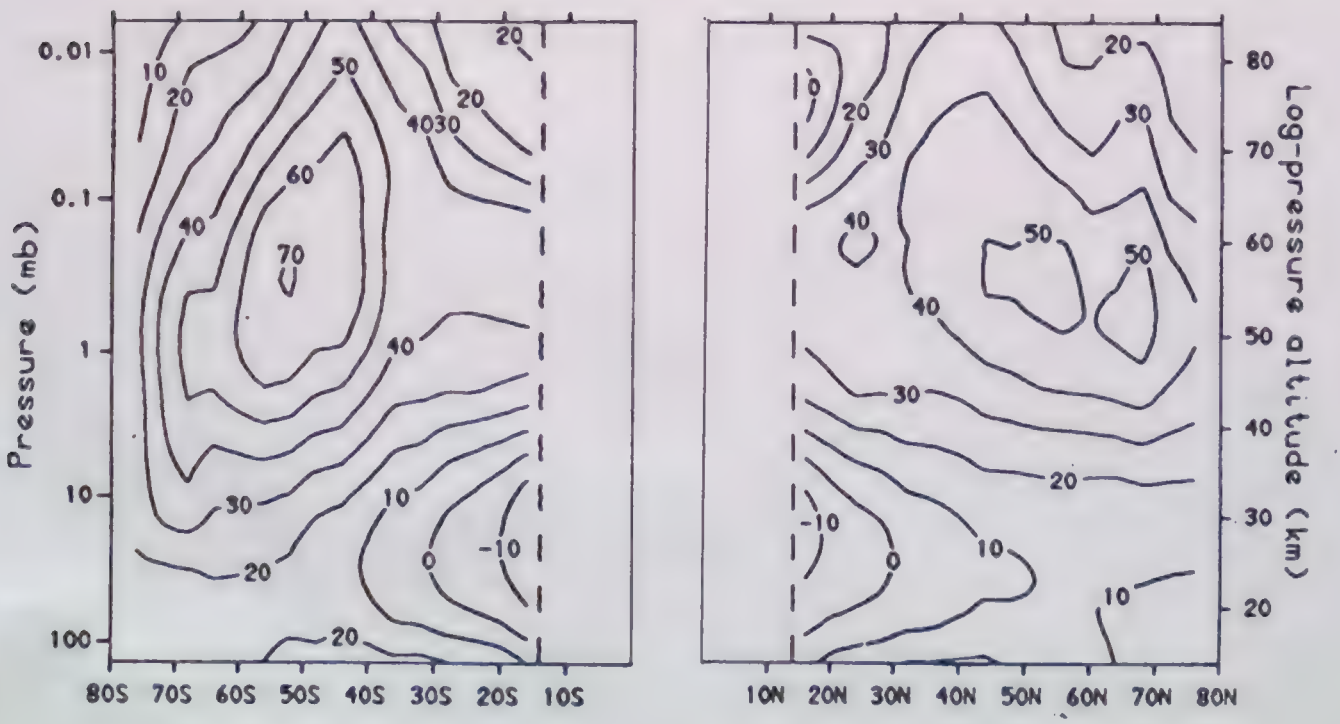
Fig 2b



Southern hemisphere: October

Northern hemisphere: April

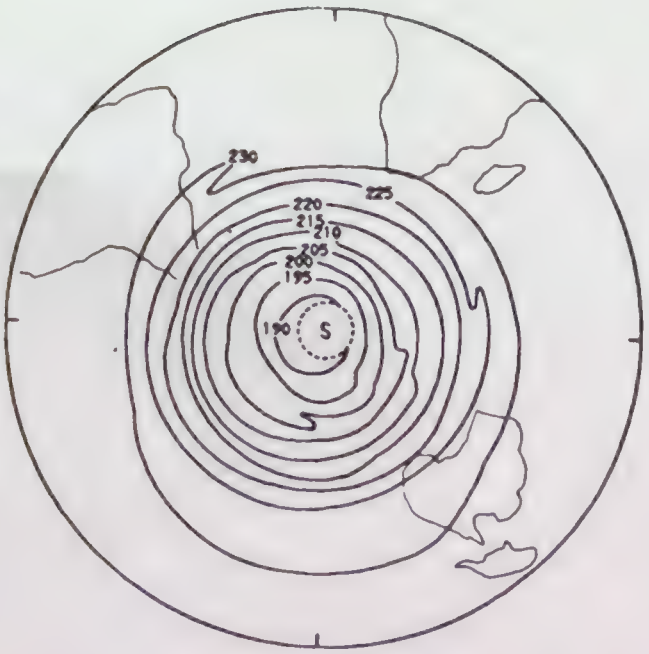
Fig 2c



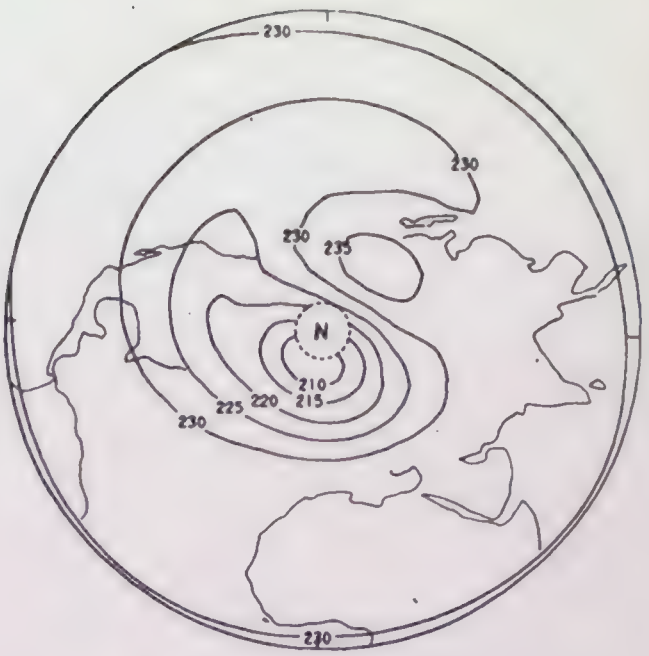
Southern hemisphere: April

Northern hemisphere: October

Fig 2d

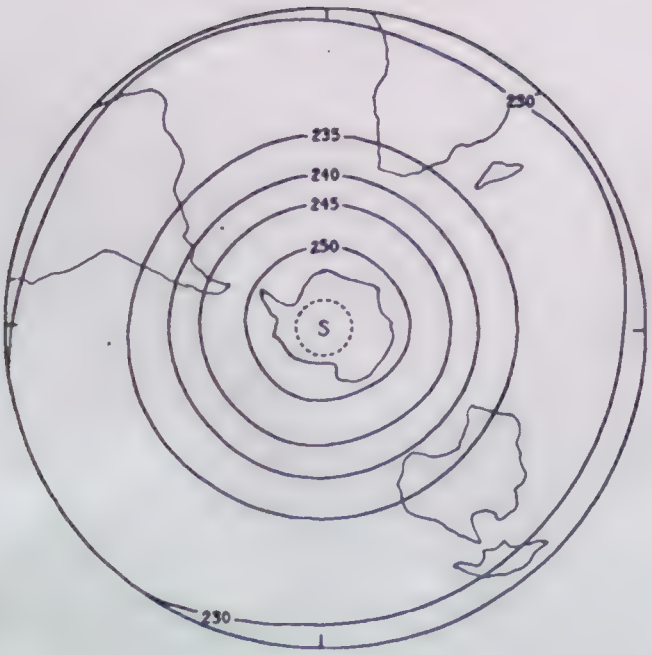


Southern hemisphere: July

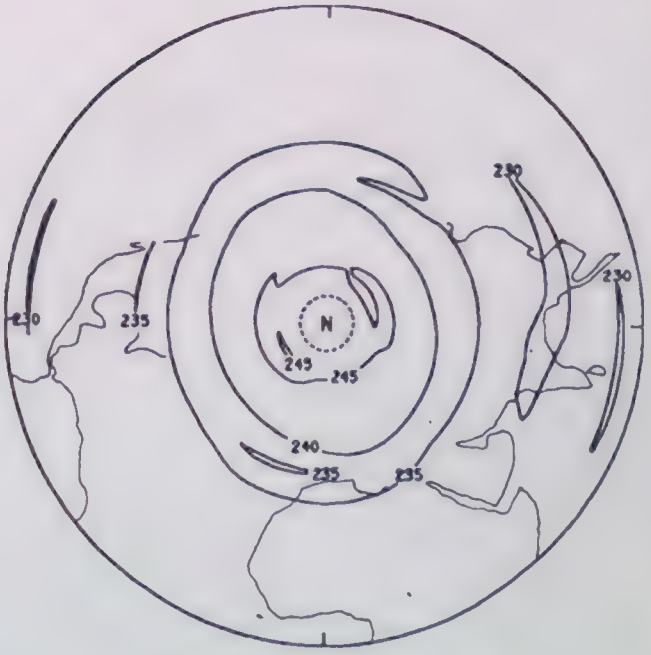


Northern hemisphere: January

Fig 3a

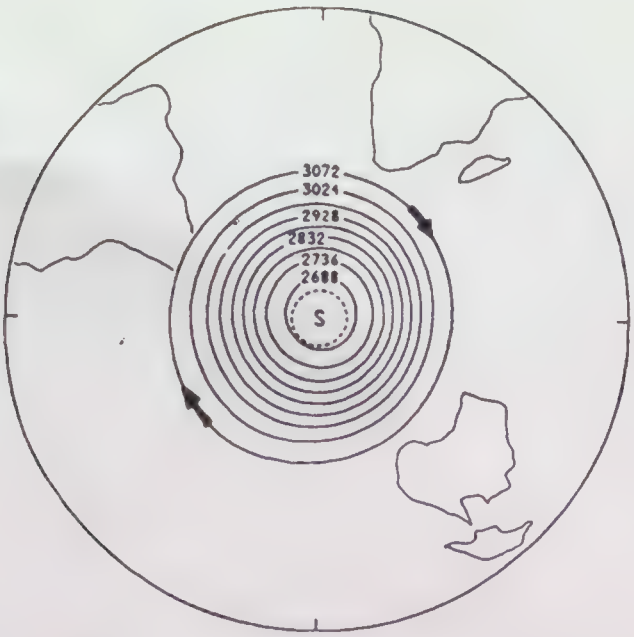


Southern hemisphere: January



Northern hemisphere: July

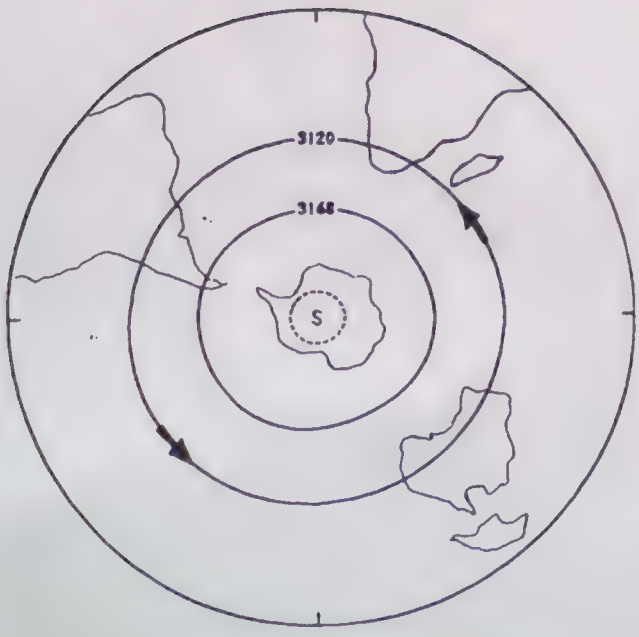
Fig 3b



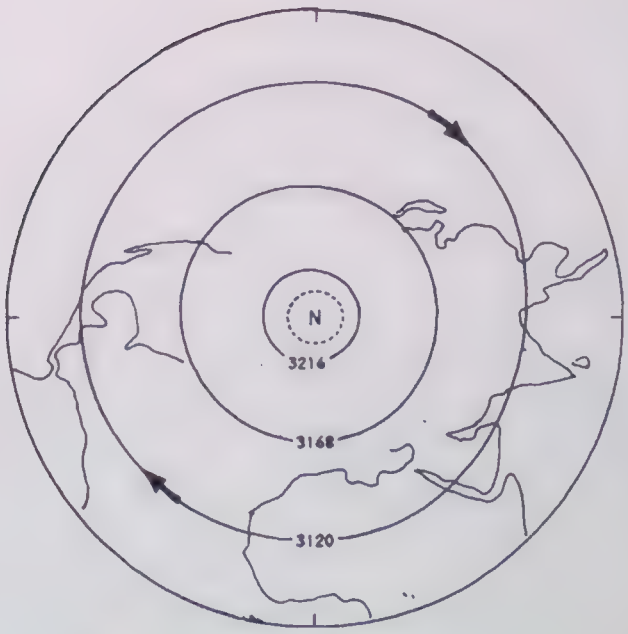
Southern hemisphere: July

Northern hemisphere: January

Fig 4a



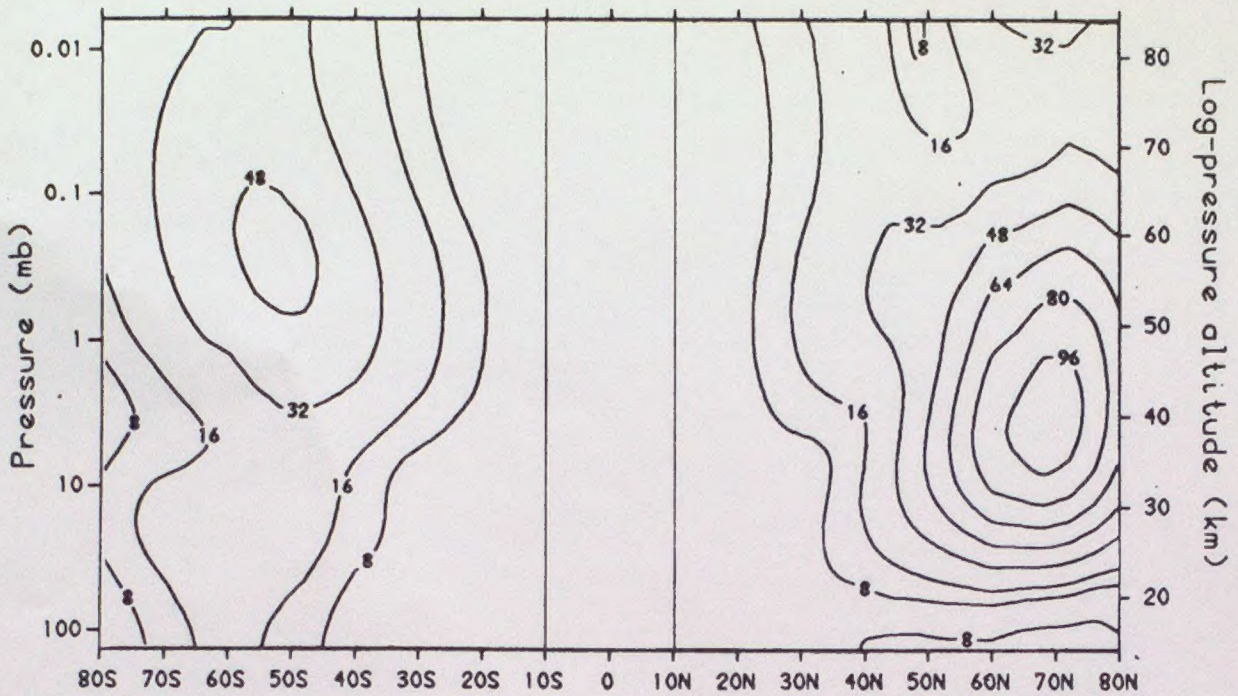
Southern hemisphere: January



Northern hemisphere: July

Fig 4b

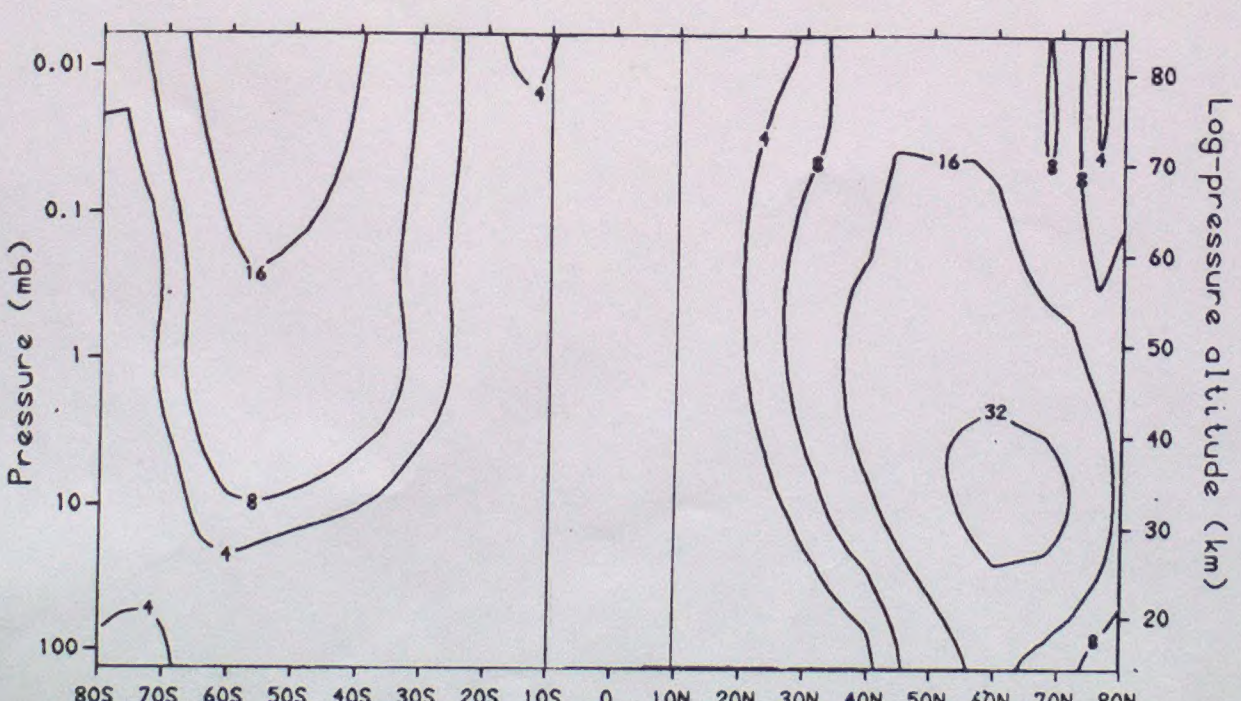
(a) Geopotential height amplitude : wave number 1



Southern hemisphere: July Northern hemisphere: January

Fig 5a

(b) Geopotential height amplitude : wave number 2



Southern hemisphere: July Northern hemisphere: January

Fig 5b

Geopotential height phase (deg. E) : wave number 1

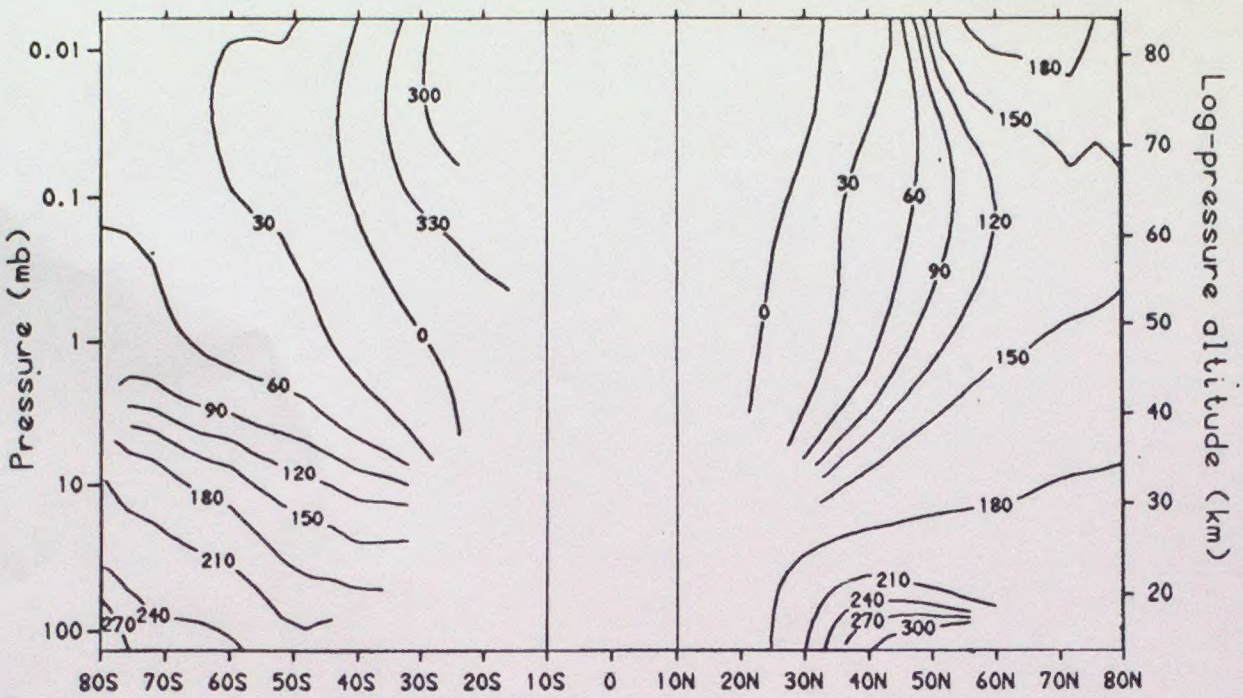


Fig 6

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